Monolithic HBV-based 282 GHz Tripler with 31 mW Output Power

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***Abstract*— We present a heterostructure barrier varactor multiplier at 282 GHz. The tripler chip was monolithically fabricated in the InGaAs/InAlAs material system on InP as carrier substrate and mounted in a fix-tuned, waveguide block. Standard rectangular waveguides WR-10/WR-3 connect the multiplier chip to the respective input/output of the waveguide block. Measurements produced 31 mW of output power and a minimum conversion loss of 11.6 dB (7 % efficiency). The device dimensions and their electrical and thermal influence are also presented.**

***Index Terms*— heterostructure barrier varactors, frequency multipliers, millimeter wave integrated circuits, indium phosphide**

I. Introduction

THE last two decades have seen an increasing demand for compact, room-temperature, medium and high power sources in the THz frequency window (0.1-10 THz). Emerging THz applications in radio-astronomy, biology/medicine, security imaging, process monitoring, wireless communication, radar and sensing are dependent on the availability of suitable THz sources. Electronic solid-state technology such as the Gunn diode, impact ionization avalanche transit time (IMPATT) and transistor amplifiers/oscillators provide sources from the low frequency side. Especially, recent advances in transistor-based MMIC amplifiers have resulted in watts/milliwatts of power at millimeter/submillimeter frequencies [1]. Meanwhile, this availability of high power amplifiers has facilitated state-of-the-art output powers reaching several tens of milliwatts at submillimeter waves using two-terminal, passive multiplers [2]. These multipliers use inherently nonlinear Schottky or heterostructure barrier varactor (HBV) [3] diodes to generate higher order harmonics from a low frequency signal. An output power of 27 mW at 296 GHz [4] has been reported for a Schottky tripler using a diamond bonded membrane. By exploiting four power-combined chips, 45 mW at 300 GHz has been achieved [2]. Fix-tuned HBV triplers have demonstrated 6.5 mW at 270 GHz, while 9.5 mW at 290 GHz has been accomplished using a mechanical tuner [5].

An advantage of using the HBV is its symmetrical/anti-symmetrical C-V/I-V, whereby even-order modes are suppressed and unbiased operation is possible. These attributes simplify the embedding circuitry and facilitate up-conversion of the input frequency to higher harmonics [6]. Since the HBV is realized in semiconductor material it is possible to epitaxially grow the diode structure in repeated series and thereby scale the power handling for a single device. Also, by choosing a monolithic circuit approach [7], employing one single chip, the processing complexity is reduced as well as alleviating alignment and assembly.

Initially, this paper describes the design of the multiplier and exemplifies existing compromises at device level. This is then followed by a brief description of the fabrication process. We then account for how the RF measurements were conducted and present the measured results.

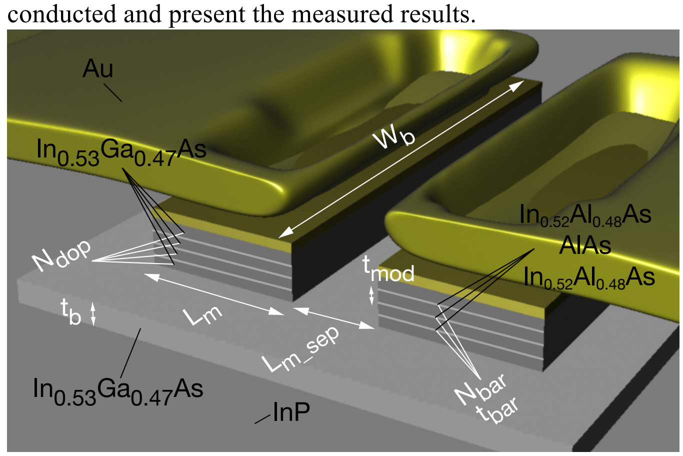

Fig. 1. Schematic of the two-mesa HBV device with material composition and critical design proportions marked.

II. Design and Fabrication

The multiplier was designed at the device, circuit and waveguide level using commercial software such as 3-D electromagnetic and thermal solvers in conjunction with nonlinear circuit analysis.

At the device level the geometry parameters of the HBV were optimized to maximize the output power at the available input power. Fig. 1 shows noteworthy dimensions of the HBV device. Several of these parameters are compromises between

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properties such as series resistance, fabrication complexity, material quality, voltage handling, thermal management and capacitance. All of these factors influence the final performance in terms of multiplier output power. Table 1 lists the parameter values for this work and their affected properties. For example, increasing the number of grown barriers, N_{bar}, will increase the maximum voltage that can be applied on a single mesa, but this also increases the series resistance and reduces the capacitance. In addition, since the bulk of the mesa consists of InGaAs, which has relatively poor thermal conductivity, a thick epitaxy will limit the power handling ability [8] due to thermally self-induced current leakage [9]. A method to avoid thick mesas is to use several mesas in series N_m [3] and thereby achieve a large number of total barriers whilst growing a thin epitaxy. This limit on the epitaxy also concerns the InGaAs buffer layer thickness t_b that connects the mesas. On the other hand, an overly thin buffer layer would increase the total series resistance and thus degrade efficiency [10].

TABLE I
HBV DEVICE DIMENSIONS

Parameter	Value	Description	Affected property
N_{bar}	3	Number of barriers	maximum voltage capacitance series resistance thermal resistance
t_{bar}	13 nm	Barrier thickness	maximum voltage leakage current [11] capacitance
t_{mod}	250 nm	Modulation layer thickness	series resistance maximum voltage
N_{dop}	10^{17} cm^{-3}	Modulation layer doping	series resistance maximum voltage
N_m	2	Number of mesas in series	maximum voltage series resistance thermal resistance
L_{m_sep}	3 µm	Mesa separation	series resistance
W_b/L_m	3.3	Mesa aspect ratio	series resistance thermal resistance
$W_b x L_m$	160 µm^2	Mesa area	power handling capacitance series resistance thermal resistance
t_b	1 µm	Buffer layer thickness	series resistance thermal resistance

The thermal resistance and electrical impedance of the HBV diode was assessed using 3-D FEM simulations (COMSOL Multiphysics) and experimental extraction through DC and S-parameter measurements.

The optimal embedding impedances at the pump frequency (94 GHz) as well as at the output frequency (282 GHz) were evaluated using harmonic balance (HB) simulations in the Agilent ADS circuit simulator. This also included electro-thermal HB simulations [12] to optimize the HBV diode area and layout in terms of output power considering the budgeted input power.

The surrounding micro-strip circuitry was designed using an electromagnetic solver (Ansys HFSS) at the aforementioned frequencies. A micrograph of the monolithic circuit is shown in the lower inset of Fig. 2. The different waveguide elements consist of input and output waveguide-probe transitions and matching micro-strip circuitry. S-parameters were exported from this solver back to the HB simulations to ensure self-consistency. The enclosing waveguide pathways and waveguide block were also designed using HFSS with a standard rectangular waveguide input/output of WR-10/WR-3.

TABLE II
HBV EPITAXIAL LAYER STRUCTURE

Rep.	No	Material	Thickness [nm]	Doping [cm^{-3}]	Description
	22	$In_{0.53}Ga_{0.47}As$	400	$>10^{19}$	Contact
	21	$In_{0.53}Ga_{0.47}As$	250 (t_{mod})	10^{17}(N_{dop})	Modulation
	....	...	...	...	...
3x	8	$In_{0.53}Ga_{0.47}As$	5	Undoped	Spacer
3x	7	$In_{0.52}Al_{0.48}As$	5	Undoped	Barrier
3x	6	AlAs	3	Undoped	Barrier
3x	5	$In_{0.52}Al_{0.48}As$	5	Undoped	Barrier
3x	4	$In_{0.53}Ga_{0.47}As$	5	Undoped	Spacer
3x	3	$In_{0.53}Ga_{0.47}As$	250 (t_{mod})	10^{17}(N_{dop})	Modulation
	2	$In_{0.53}Ga_{0.47}As$	1000 (t_b)	$>10^{19}$	Buffer
	1	$In_{0.53}Ga_{0.47}As$	100	Undoped	Spacer
	0	InP		SI	Substrate

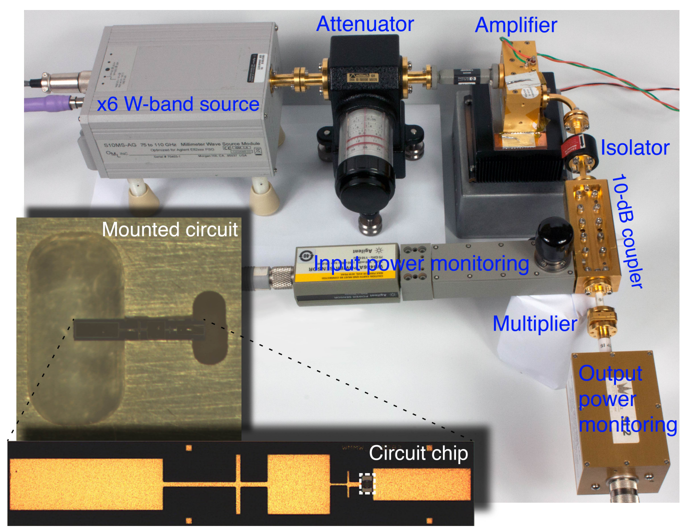

Fig. 2. Measurement setup for characterizing the tripler input and output. The top inset shows a micrograph of the mounted microstrip circuit connecting the WR-10 and WR-3 waveguides. The lower (magnified) inset displays the multiplier chip with the microstrip circuit in detail. A white dashed rectangle marks the HBV device from Fig. 1.

The HBV 3-barrier structure was MBE grown (molecular beam epitaxy) in the material system InP/InAlAs/InGaAs. Table 2 presents the material structure of the three-barrier HBV epitaxy, where layer numbers 3-8 were repeated three times. A maximum capacitance of C_0=2.6 fF/um^2 and breakdown voltage of over 6 V per barrier was measured. The fabrication of the HBV MMICs is based on standard III-V processing that was developed for discrete devices [13],[3], with an additional electro-plating step to include the circuit on the InP substrate. The wafer was sawed and lapped into

1700x310x30 μm multiplier circuit chips as featured in the lower inset of Fig. 2. These chips were mounted in a waveguide block, as shown in the top inset of Fig. 2, which is split in the plane of the propagation direction of the rectangular waveguides. The block dimensions are 18x20x6 mm.

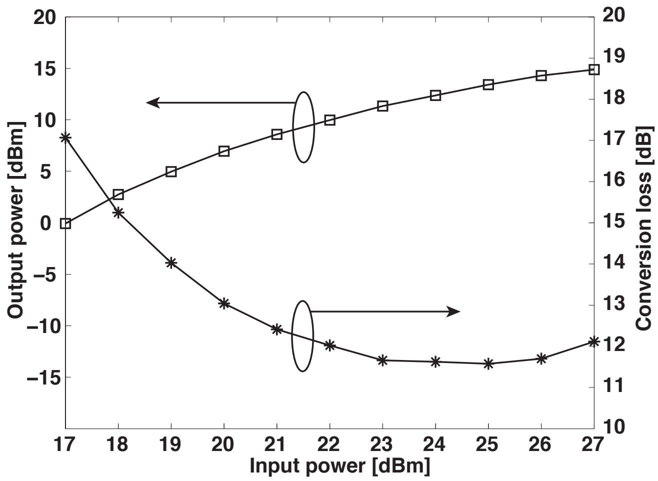

Fig. 3. Output power and conversion loss at 282 GHz versus input power for the HBV tripler.

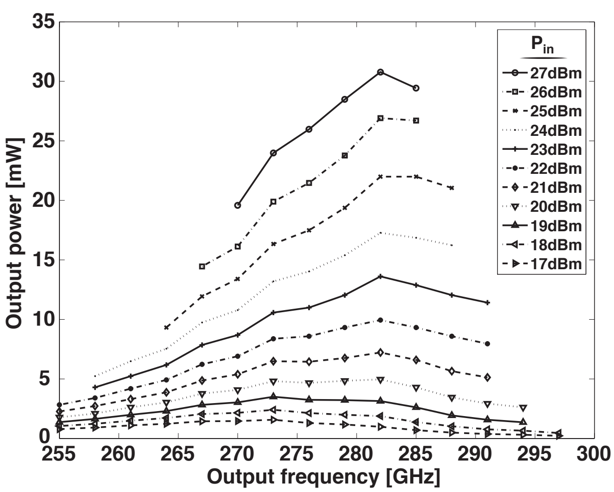

Fig. 4. Frequency sweep at constant input powers (17-27 dBm, 1 dB increments) versus output frequency for the HBV tripler.

III. Results

Evaluation of the assembled multiplier block was done using the setup shown in Fig. 2. An Agilent RF-generator (15.67 GHz) feeding a x6 frequency extender was used as pumping source. This is followed by an attenuator, which is used to control the 94 GHz input into a Quinstar QPN-94023025 1 W amplifier biased at 5 V and typically 5 A. At the output of the amplifier an isolator is placed to avoid back reflected power, connecting a 10 dB coupler. This coupler is used to monitor the power into the multiplier concurrently using an Agilent W8486A power sensor, thereby avoiding erroneous measurements due to amplifier gain drift between calibrations. The coupler output is connected to the input of the multiplier block. An Erickson PM4 detector is connected to the multiplier output to measure the 282 GHz signal.

We can see in the power sweep of Fig. 3 that the maximum output power is 14.9 dBm (31 mW) at 27 dBm (500 mW) input power. A minimum conversion loss of 11.6 dB (7% efficiency) is attained at 25 dBm (316 mW) input power. In Fig. 4 we have plotted frequency sweeps at different input power levels from 17 to 27 dBm with a peak output power at 282 GHz.

IV. Conclusions

The design, fabrication and characterization of a monolithic HBV tripler at 282 GHz has been presented. A maximum output power of 31 mW was measured for the multiplier. This is a clear improvement for HBVs at these frequencies and comparable to the performance of Schottky based multipliers. These results are limited by the available input power and could provide a high power stepping-stone for THz multiplication.

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